LANSCE BEAM INSTRUMENTATION AND THE LANSCE REFURBISHMENT PROJECT

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Abstract

The heart of the LANSCE accelerator complex consists of Cockroft-Walton-type injectors, a drift-tube linac (DTL) and a coupled-cavity linac (CCL). These systems are approaching 40 years of age and a project to re-establish high-power capability and to extend the lifetime is underway. Many of the present beam diagnostic systems are difficult to maintain, and the original beam position monitors don't provide any data at all. These deficiencies hamper beam tuning and trouble-shooting efforts. One thrust of the refurbishment project is to restore reliable operation of the diagnostic systems. This paper describes the present diagnostic systems and their limitations and the envisaged next-generation systems. The emphasis will be on the uses and requirements for the systems rather than the solutions and engineering aspects of the refurbishment.

INTRODUCTION

Figure 1 is a diagram of the accelerator complex at the Los Alamos Neutron Science Center (LANSCE). Presently protons and H^- ions are delivered to five experimental areas. The facility was originally designed for performing nuclear physics experiments with pions, muons and protons as probes with a primary beam power of 1MW. We currently produce about 125kW of beam power at one-half of the original duty factor due to a change of mission and aging of the system. The LANSCE-R (refurbishment) project aims to restore the higher-power operation and to ensure the on-going reliable operation of this accelerator facility.

One thrust of the LANSCE-R project is to extend the lifetime and restore reliable operation of the beam diagnostic systems in the linac. Some of the present systems are difficult to maintain, and the original beam position monitors (BPMs) do provide any data at all.

The large beam power and the various beam time-structures required at the experimental areas provide challenges in making diagnostic systems that can be used for production operations. The following sections describe the various beam conditions that drive the requirements for performance of the diagnostic equipment.

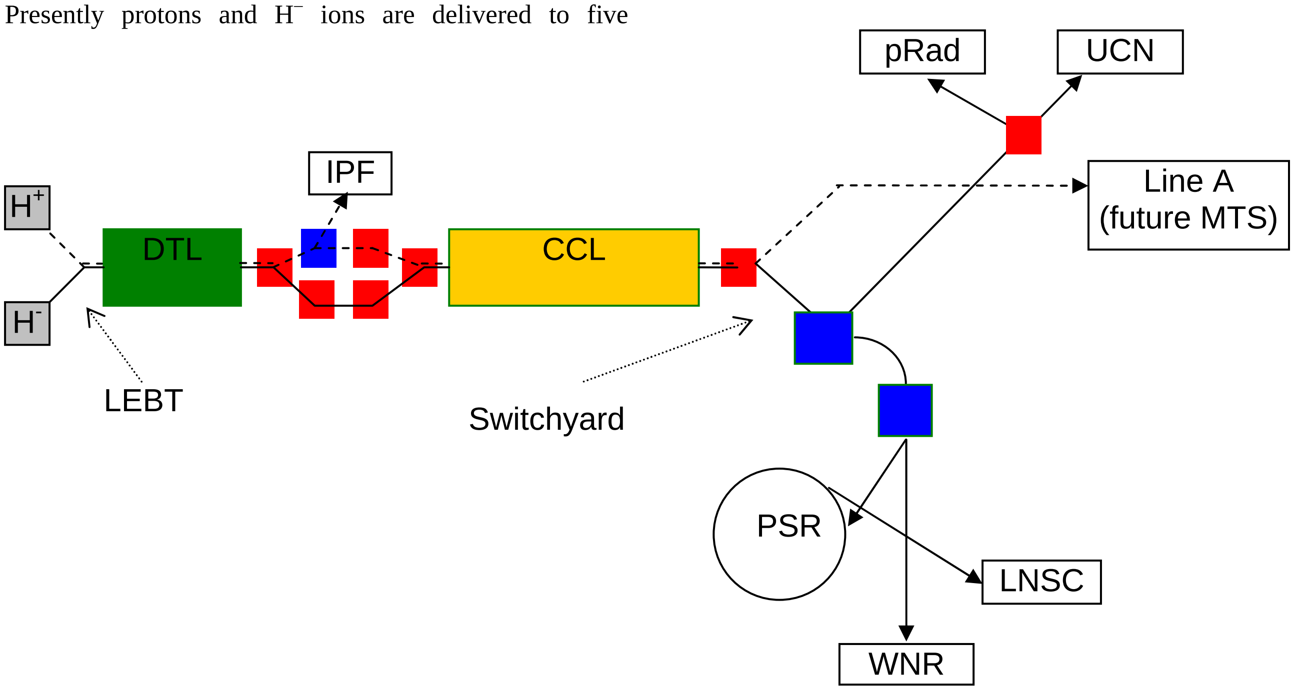

Figure 1: Schematic depiction of the LANSCE accelerator and experimental areas. Proton (H^+) beam lines are shown as dashed lines and H^- beam lines are shown as solid lines. The Low-Energy Beam Transport (LEBT) merges the two beam species and directs them into the linac. The beam switchyard, just downstream of the linac, directs beam to the various experimental areas. Blue squares denote pulsed magnets for switching beam delivery on a per macropulse basis. The experimental areas are: IPF: Isotope Production Facility; pRad: Proton Radiography; UCN: Ultra-Cold Neutrons; MTS: Materials Test Station (under development); LNSC: Lujan Neutron Scattering Center; WNR: Weapons Neutron Research. The beam to the LNSC is compressed in the Proton Storage Ring (PSR).

LANSCE REFURBISHMENT

The LANSCE-R project aims to restore the capability for high-power (1MW) beam operation and to ensure the continued reliable operation of the LANSCE accelerator. The scope of the refurbishment is limited to the core accelerator driver common to all experimental facilities, i.e. the injectors, linac and beam switchyard. Included are: linac radio-frequency (RF) systems, control and timing systems, DC magnet power supplies, water systems, vacuum systems, beam deflectors, spare drift tubes for the DTL, and some beam diagnostics. Because the control systems interact with nearly every other system, changes will be required for even those components not explicitly within the scope of the refurbishment.

The diagnostic systems to be refurbished are: beam position monitors, beam phase monitors and wire-scanner beam profile monitors. Those not included, but requiring new interfaces to the control system are: beam current monitors, beam loss monitors, collimator current monitors, multi-wire beam profile monitors, slit-and-collector phase-space measurement systems, and energy-discriminating beam absorber/collector systems.

Drivers for Requirements on Diagnostics

The requirements on performance of diagnostic systems are driven by two rather different sets of beam conditions: 1) Initial tune-up after long outages, and 2) Production operations. The major differences between these two sets of conditions lie in the time-structures of the beams; these will be described in the following sections.

The beam diagnostics also serve two distinct purposes: 1) Determining the setpoints of the accelerator equipment that result in optimum beam transport, and 2) Diagnosing problems with accelerator equipment. The second purpose will drive requirements on the bandwidths and data rates from the diagnostic systems.

BEAM TIME-STRUCTURES

After a long maintenance outage of several months we perform an initial tune-up with 150μs-long beam pulses whose peak currents are 1mA to 10mA. For these tune-ups fairly modest performance is required of the diagnostic systems. One of the most important requirements is long-term stability of the measurements; for example the beam position and angle at the injection to the CCL should be repeatable year-to-year.

For production operations, additional time-structure is imposed on the beams; these complicate the measurements and also invoke requirements on synchronization of measurements with the beam time-structure. In this section the time structures of the beams are described.

Three time-structures are germane to the diagnostic systems and will be described here: macropulses, minipulses and micropulses.

Macropulses

Presently, for production operations, macropulses occur at a rate of 60Hz and last typically 625μs, though one goal of LANSCE-R is to restore the original macropulse rate of 120Hz. During a macropulse the RF accelerating fields in the linac are present and stable, pulsed magnets are in their necessary states, and the ion sources are producing beams; in short, the accelerator is "on". Both protons and H^- ions can be accelerated simultaneously but each beam species is delivered to a single experimental area during a given macropulse.

Of the 60 macropulses that occur in one second, 20 are for H^- beam to the Lujan Neutron Science Center (LNSC), and 40 are for protons to the Isotope Production Facility (IPF) and H^- to the Weapons Neutron Research facility (WNR). Individual macropulses are sent on demand to the Proton Radiography facility (pRad) or to the Ultra-Cold Neutron experiment (UCN); these macropulses are substituted for IPF/WNR macropulses.

These combinations of beam species and destinations are known as beam "flavors." An important capability of the diagnostic systems is to associate measurements with beam flavors. Presently we set up the timing system to trigger data collection on particular beam flavors' macropulses; the upgraded systems will need to have a similar capability, and may offer greater flexibility in this regard.

Another aspect of macropulses that impacts diagnostic performance is the macropulse length. In particular the L/R time constants for transformer-type beam current monitors must be much longer than the macropulses to allow accurate measurements.

Micropulses

In radio-frequency accelerators beam particles are accelerated during a particular part of the RF cycle; the resulting beam consists of a train of bunches (micropulses) at the frequency of the accelerating field. The initial stage of acceleration at LANSCE is in a DTL operating at 201.25MHz. Each micropulse contains a few $\times 10^8$ ions and is 50-100ps long.

This micropulse structure provides a strong narrow-band signal that is useful in some beam diagnostics, particularly beam position monitors.

Minipulses

In the low-energy beam transport (LEBT) for the H^- beam, where the beam energy is 750keV, a travelling-wave beam chopper can impose on the beam time-structures on the scale of tens of nanoseconds.

For long-bunch (LB) beam to the Proton Storage Ring (PSR), whose ultimate destination is the LNSC, the minipulses are about 300ns long and have a frequency of 2.8MHz. This provides a gap in the accumulated beam that allows time for a pulsed kicker to turn on to extract the beam from the PSR. For WNR, ~20ns-long minipulses are pre-bunched and each is accelerated in a single DTL RF cycle to yield intense single-micropulse pulses. For beam to pRad a variety of minipulse patterns are used, but usually a 100ns-long precursor pulse is followed a few hundred microseconds later by several 60ns-long minipulses.

The frequencies and lengths of all of the minipulses can be modified to suit users' needs or to modify the average beam current to allow operators to cope with varying conditions of the accelerator. These adjustments are frequently made, and beam diagnostics need to provide useful data under these conditions.

BEAM POSITION AND PHASE MONITORS

There are presently two separate systems for measuring the phase and the transverse position of the beam. The beam phase measurement is used solely in the Δt tuneup procedure [1]. This procedure is carried out with unchopped beams and the system has no provision for synchronizing the phase measurement with the minipulse structure; thus the system is not useful for H^- beams during production operations. A transducer for the present system is shown in Figure 2. It is a metal cylinder about 1cm long with a diameter of about 5cm, which is the diameter of the beam pipe in this area. This cylinder couples capacitively to the beam; the 201.25MHz signal induced by the micropulse structure of the beam travels via a TNC connector and a solid-shield cable to the phase measurement instrumentation. The phase measurement is an I and Q measurement relative to a sample of the 201.25MHz reference oscillator for the DTL [2]. The response of these transducers is sensitive to the transverse position of the beam; reducing this sensitivity is desirable in the new system.

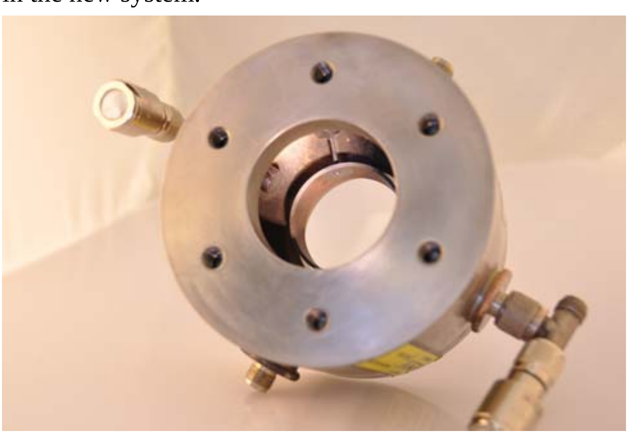

Figure 2: Photograph of a present transducer module for beam phase measurements.

The present transducer module for the beam position measurements is shown in Figure 3. Each transducer is a rigid wire with one end soldered to the beam pipe and the other end connected to the center conductor of a cable via a TNC vacuum feed-through connector. This is a so-called "B-dot" transducer, as the time rate of change of the beam-induced magnetic field through the loop induces the signal. ($\dot{B} \equiv \partial B / \partial t$.) There is presently no functioning instrumentation to provide data from this system.

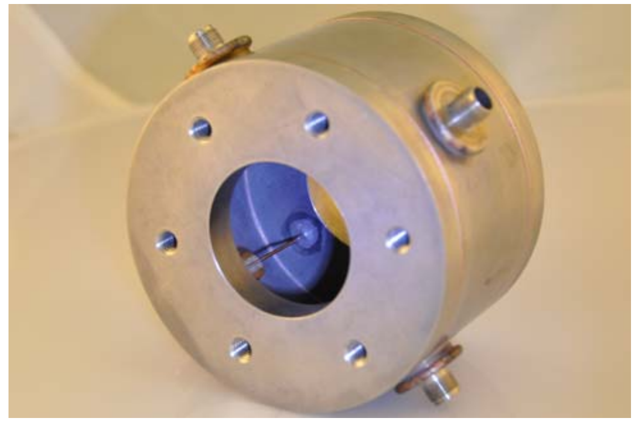

Figure 3: Photograph of a present transducer for beam position measurements.

In the new system under development for LANSCE-R a single set of transducers will provide signals for the phase and position measurements. A prototype transducer is shown in Figure 4. It is a stripline-type electrode with one end grounded to the beampipe. Signal formation can be understood in terms of image currents [3].

These new transducers are designed to fit into the locations of the existing transducers for the Δt and BPM systems.

Figure 4: Photograph of a prototype transducer for the new beam position and phase measurement system.

BPPM Requirements

Table 1 shows requirements for the BPPM system. The resolutions shown in this table will be achievable only with unchopped beam (no minipulse structure) and after 100μs of steady beam conditions. This corresponds to tune-up conditions, where precision is most valuable.

Phase and position measurements are required for beams with minipulse structures but with relaxed requirements on accuracy and precision. Synchronization with the minipulses is necessary so that measurements are made at a specific time during the minipulses; this will require distribution of the minipulse reference oscillator signal to the BPPM systems or it may be possible to use events from the timing system, or triggering from the beam signal itself with an adjustable delay. Synchronization among the BBPMs, to provide a measurement from many devices of the same time-slice of beam, is also of great value.

The system will be able to report data on a per-minipulse basis for H^- beam to the proton storage ring, i.e. at 2.8MHz; this allows correlation of data with existing downstream diagnostic systems.

For the H^- beam to WNR, which normally has single-micropulses spaced at 1.8μs, measurements are difficult. An existing downstream system has this capability, so the inclination is to require it for the new system in the linac, but cost/performance trade-offs must be considered. A requirement for measurements of this type of beam is still under consideration.

Table 1: Requirements for the BPPM system.

Parameter	Value
Frequency of Measurement	201.25 MHz
System Response Time	50 ns
Averaging Window for System Resolution Specifications	100 μs
Position Resolution (% of radius, RMS)	0.46% (0.1mm)
Position Accuracy (% of radius)	±4.6
Position Range (% of inner electrode radius)	±60
Phase Resolution (RMS)	0.25°
Phase Linearity	±2°
Beam Current Resolution (RMS)	0.05 mA
Beam Current Accuracy	N/A
Beam Current Range	0.9 to 21 mA
Timing Uncertainty	±50 ns

For unchopped beams, such as the proton beam to IPF, the system should be able to measure at a rate of about 1MHz.

Of great importance, both for tune-ups and for equipment trouble-shooting, is the long-term stability of measurements. For example, measuring the beam position and angle at the injection to the CCL then using those same parameters for the tune-up the following year is very valuable. The requirements on accuracy should address this issue. The plans for this system provide for easy in-situ calibration with no manipulation of the hardware by sending signals to each electrode and picking them up on the others.

Another mode of data reporting that will be required is a single measurement, at a fixed time during each of many macropulses for a given beam flavor. This allows one to observe variations in conditions on timescales of several seconds. This capability in other diagnostic systems has proven to be very valuable.

BPPM Locations

BPPMs will be installed after DTL modules 2, 3 and 4, and one will be installed in the beam transport between the DTL and CCL. BPPMs will also replace the 28 existing Δt transducers in the CCL, and an additional two BPPMs will be located in the CCL to allow characterization of the injection parameters of the beam.

BEAM PROFILE MONITORS

Scanning-wire-type beam profile monitors [4] are currently used throughout LANSCE for tune-up and trouble-shooting. Replacement of many in the linac and some of those in the beam switchyard is included in the scope of LANSCE-R. Several in the linac will be removed.

A photograph of the type of transducers used in the present systems is shown in Figure 5. The wires are crossed and the actuator is mounted 45° from vertical; both horizontal and vertical profiles are measured with a single actuator. The crossed wires can complicate the measurement, especially for H^- ions, as secondary electrons from one wire can induce signal on the other.

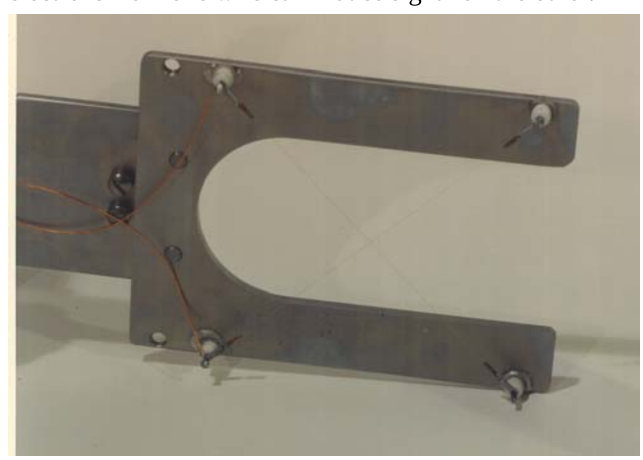

Figure 5 Photograph of a present wire-scanner fork. Note that the wires cross near the center of the aperture.

Most of the wire-scanners in the linac use 125μm-thick tungsten wires. When scanning, this material produces a great deal of localized beam spill; so much that these devices cannot be used under production conditions, greatly limiting their value in trouble-shooting. These tungsten wires rarely break, however. The wire-scanners in the beam switchyard use more fragile 100μm-thick SiC fibers; most can be run during production operations.

In addition to the wire thickness and material, the time the wire stays in the beam contributes to the beam spill produced during a scan. The present system is controlled by a centralized computer through an antiquated control system, with data and commands issued on a per-step basis. The speed of data and commands, as well as the nature of the motor controllers, results in scans that are slower than ideal. The upgraded system will be controlled by a dedicated local computer interacting directly with the devices and data will be reported on a per-scan basis. The motor control will be optimized for rapid scanning and accurate wire positioning.

Table 2: Requirements for the wire-scanner system.

Parameter	Value
Sensing Wire or Fiber Materials	SiC, W, or C
Sensing Wire or Fiber Diameters (mm)	<0.15
Minimum Distribution Horizontal or Vertical Width, rms (mm)	1.0
Minimum Projected Distribution Bin Width (mm)	0.1
Typical Minimum Beam Macropulse Length (μs)	150
Typical Repetition Rate (Hz)	4
Minimum/Maximum Peak Secondary Electron Emission Current (μA)	-1/-2000 & +0.01/+500
Distribution Minimum Peak-to-Edge Ratio	100:1
Amplifier Response Time Constant (μs)	~10
Maximum Sampling Rates within a Single Macropulse (MS/s)	0.1
Linear Peak Actuator Velocity, under Closed Loop Control (mm/s)	>8
Wire Location Repeatability or Precision (% rms distribution width)	<10
Absolute Wire Location Accuracy (mm)	1
Peak Beam Current Range (mA)	21 to 0.9
Timing System Resolution (ns)	~ 100

Requirements on the wire-scanner parameters are shown in Table 2. These parameters are driven by the need to use the wire-scanners in tune-up and production conditions and to provide performance at least as good as that from the present systems. The upgraded systems should provide measurements during both tune-up and production if possible. RMS beam-spot sizes to be measured are a few millimeters. Step sizes of 0.1mm will provide a good sampling density for these profiles.

With 100kSamples/second, the system will be able to provide average beam profiles as a function of time along macropulses. This kind of measurement is not possible with the present system except by running many scans with different timing specifications, a very labor-intensive effort.

The upgraded system should have the wires oriented in a way that prevents cross-talk between the wires. Figure 6 shows the proposed scheme; this is already used in some H^--specific beamlines and is found to be effective. This arrangement requires a longer stroke than that shown in Figure 5.

We don't anticipate a need for synchronization with minipulses and among devices for this system, as changes in beam profiles at LANSCE typically occur on the scale many microseconds.

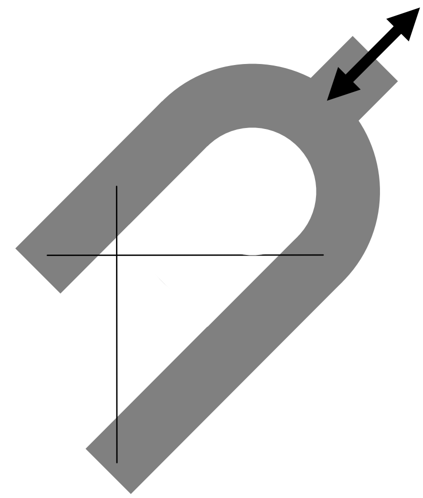

Figure 6 Wire locations on the actuator fork to eliminate cross-talk between the wires. The crossing point of the wires needs to be outside the beam-pipe aperture.

OTHER DIAGNOSTIC SYSTEMS

The BPPMs and wire-scanners are the only two diagnostic systems to be replaced on a system-wide basis under LANSCE-R, but because the control system is to be replaced the interfaces to the control system will need to be replaced for the remaining diagnostic systems. The diagnostics presently interface with the control systems via RICE (Remote Instrumentation and Control Equipment). The interface includes analog-to-digital converters, binary indications and pulse commands to control and read the measurements. Programs run on centralized computers and synchronization is effected through a multi-layer scheme of networks and computer buses. The new control system will be based on EPICS (Experimental Physics and Industrial Control System) with device-level computers controlled by and serving data via a network to applications requesting those services.

The individual systems are described in the following sections; a summary and comparison of these systems follow the descriptions.

Slit-and-Collector Beam Phase Space Measurement System (EM)

There are ten slit-and-collector [5] systems for measurements of transverse beam phase-space distributions; each can measure in the vertical and horizontal planes. The slit and the 76-wire collector step together across the beam, so in the present system coordination of motor and data collection results in a great deal of communication between the user's computer and the device-level systems. The present system is multiplexed, with a small number of motor controllers, amplifiers and analog-to-digital converters. Some of the multiplexing is effected electronically, but the signals from the wires to the amplifiers are swapped manually by moving cable connectors.

The plan for the refurbishment is to field a device-level computer that will perform coordination of device motion and data collection and will pass to the user scan-level data sets. The system may be multiplexed, but the preference is to move toward a single electronics chain per channel.

Harps (HP)

There are 17 multi-wire beam profile measurement systems [6] in the injector/linac area; each measures horizontal and vertical profiles with 76 thin wires. The devices can be inserted and retracted, but no coordination between motion and data collection is required, as the device is in a fixed location for an entire data-collection cycle. The electronics chains are those also used for the EM system described above; in total there are 74 motors and about 4100 signal wires included in these systems.

The plan for these devices is to implement a new interface to the control system along with the EM systems as described above.

Absorber/Collector (AB)

This system is used for the initial tune-up of some of the RF systems' setpoints. There are four sets of these devices; each absorber, when inserted into the beam-pipe, allows protons of some minimum energy to pass to the collector (Faraday cup), while protons below that energy are stopped. A relatively small number of data channels for motion control and data collection are required and the volume of data is small.

Beam-Current Monitors (CM)

Transformer-type beam current monitors [7] are present along the injector/linac area. These are used to monitor beam transmission and some provide inputs to the machine protection system. Beam current measuements need to be associated with their respective beam flavors. Some of the amplifiers for these devices have selectable gains.

Beam-Loss Monitors (AP, LM)

Cans of liquid scintillator viewed by photomultiplier tubes detect ionizing radiation produced by beam particles that escape the beam vacuum envelope. Two instrumentation systems provide signals to the control system, one (AP) providing low-bandwidth signals for machine protection and refinement of machine parameters, the other (LM) providing high-bandwidth signals more useful for trouble-shooting.

Collimator Current Monitors (BA)

Collimators, both stationary and movable, are present in the low-energy beam transport area. The beam currents on these devices are measured and are available in the data system.

The motor controllers for the movable collimators are identical to those used in the EM system.

Summary of Other Diagnostics

Table 3: Characteristics that drive requirements for the interfaces to the new control system for diagnostic systems not within the scope of LANSCE-R.

	EM	HP	AB	CM	AP	LM	BA
Motor control	x	x	x				x
Signals per device	160	160	6	1	5	1	1 to 5
Timed data	x	x	x	x		x	x
Used in prod.				x	x	x	x
Inter-device Synch.				x		x	
Per-scan data	x						

Table 3 shows several characteristics that underlie the requirements for the interfaces to the new control system for diagnostic systems that aren't to be refurbished under LANSCE-R.

Motor controllers, along with their position encoders and limit switches are required for beam-intercepting diagnostics and for the movable collimators.

The EM and HP systems have many analog signals to be conditioned and digitized.

All of the systems except for APs need to deliver "timed" data, that is data collected at specific times during macropulses, or better yet, vectors of data collected along the macropulses.

Several of the systems are non-intercepting, and can be used during production operations. More flexible timing and correlation of data may be required for these systems.

Data from the CM and LM systems need to be synchronized so that data from all of the devices of each type can be taken for a particular time-slice of beam.

Only the EM systems will be required to provide data on a per-scan basis, i.e. coordinating device motion and data collection, then reporting one package of data from the scan.

SUMMARY

The refurbishment of the core of LANSCE, including some diagnostic systems and the control system, has necessitated a close look at the requirements of the diagnostic systems and the data they provide. The diagnostics should be useful for initial tune-ups as well as during production operations and should aid in setting equipment parameters, general trouble-shooting, optimization and beam studies. Flexibility in the ways that data are collected and reported is valuable, too.

While some questions remain, we have identified the major requirements for these systems and work on designing solutions is underway.

ACKNOWLEDGEMENTS

LANSCE-R is a large complex project involving many managers, administrators, scientists, engineers and technicians. Included in the list of authors of this paper are those people who have contributed to developing the requirements for the beam diagnostic systems. We gratefully acknowledge the efforts of all the people who have contributed to the progress of LANSCE-R.

This work was supported by the U. S. Department of Energy under contract DE-AC52-06NA25396.

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